Greenhouse Heating Systems

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Section 1: Introduction

For most climates, there exists at least a period of time during the year where the ambient temperatures outside are too low for crop production, or the low temperatures that occur would result in significantly reduced crop productivity. This is the primary reason behind greenhouse-based agricultural production, whether it is for ornamental plants, forestry, or vegetable crops. Therefore, providing heat energy to maintain optimal temperatures within the greenhouse (or the hotbed, growth chamber, etc.) is a critical function in greenhouse management.

Heat energy may be measured as calories, joules, or even horsepower. However, in the greenhouse industry (especially in the U.S.) it is most often measured as British thermal units (Btu). A Btu is the amount of heat energy required to raise 1 pound of water 1° F.

In greenhouse heating, heat energy must be added to the greenhouse at the rate that it is lost from the greenhouse in order to maintain the established temperature. The higher the rate of heat loss from the greenhouse, the higher the amount of heat energy that must be generated and added back to the greenhouse. There are 3 ways that heat is lost from greenhouses:

Conduction is the loss of heat energy through the glazing, metal purlins, barcaps, doors, and fans (i.e. like heat energy moving from hot coffee or soup through a spoon sitting in the coffee or soup). The vast majority of conductive heat loss is through the glazing, and most heat loss from greenhouses occurs through conduction.

Infiltration/exfiltration is the heat energy loss through cracks between or around glass panels, doors, and fans by mass airflow. Even in a well-designed "tight" greenhouse, up to 10% of total heat loss may be by infiltration/exfiltration. In older or less “tightly sealed” greenhouses, a much higher amount of heat loss may occur through infiltration/exfiltration.

Radiation is the heat energy loss due to the emission of radiant energy from a warm body (greenhouse) to a cold object (outside objects) with little warming of the air. Glass, vinyl plastic, FRP, and water do not readily allow the passage of radiant energy, whereas polyethylene film readily allows the passage of radiant energy.

Section 2: Types of Greenhouse Heating Systems

Greenhouses may utilize central heating systems or local heating systems. Central heating systems generate heat energy, most often using a large boiler, in one location, and distribute that heat energy to many locations. Local heating systems are located in the greenhouse or greenhouse section that they are responsible for heating. For large operations, a central heating system may be more efficient than a local system. However, the cost of installation and maintenance of a central heating system can be high. For smaller operations, this expense may be hard to justify. The size of the boiler unit required, the fuel source or sources available, size of the greenhouse operation, and maintenance costs all must be considered when deciding whether to use a central or local heating system.

Central Heating Systems

Central heating systems may distribute heat energy as either hot water or steam. In the former, hot water is produced in a central boiler by burning a fuel such as coal, wood chips, fuel oil, liquid propane, natural gas or various types of waste oils. Where coal and wood are used as fuels, the fuel must be mechanically or manually supplied to the boiler fire box. Where oil, propane, natural gas or other oils are used, a constant automated supply line is used to supply fuel to the boiler fire box.

Boilers are designed to have a very high Btu output capacity with most boilers having heating capacities of over 1,000,000 Btu/hr. The hot water, usually at 180° F if not pressurized, is produced in the boiler and then pumped through distribution pipes or tubes around the greenhouses. Because only 1 Btu of heat is provided by each pound of water as it cools 1° F, large volumes of water are required with a hot water-based central heating system. In addition to the pipes required for distribution of the hot water throughout the greenhouse, pumps are required to circulate the hot water through the pipes.

In some greenhouse operations, pressurized hot water is used. This allows the hot water to be delivered at a higher temperature (typically 203° F). The higher temperature allows the water to carry more heat energy which reduces the volume of water required (the higher temperature means a given volume of water carries more heat energy) and thus reduces the boiler size and plumbing required.

A central heating system may also use steam. In this system, steam is produced in the boiler. The steam then moves in pipes throughout the greenhouse. The steam moves through the pipes due to the pressure of the steam, and pumps are not required as with a hot water system. Because the steam is at a temperature of 215° F, it contains more heat energy than hot water and thus less water and piping are required as compared to a hot water-based system.

Most central heating systems use steel, copper or aluminum pipes to distribute hot water through the greenhouse. The hot water or steam heats the pipes which in turn give off the heat to the air in the greenhouse (distribution pipes are discussed in more detail under heat distribution). Others may distribute the hot water through rubber tubes placed directly in the concrete floors of the greenhouse.

The hot water-filled rubber tubes heat the greenhouse floors which in turn release heat energy to the greenhouse atmosphere. This system is referred to as floor heating or sometimes as radiant heating (not to be confused with radiant heating units discussed under "Local Heating Systems". The floor-based radiant heating system is a particularly good system where plant material is being grown on the floor since it places the heat close to the substrate (soil) and helps to maintain a warmer substrate temperature.

Some greenhouse facilities are able to take advantage of being located near electrical plants or factories that produce steam or hot water. Waste steam or hot water is diverted from the factory to the greenhouses where the heat is utilized in a central heating system. This practice is referred to as co-generation. The advantage of co-generation to the greenhouse company is that a supply of lower cost heat is obtained. The advantage to the factory or electrical plant is that the greenhouse company helps to cool the waste hot water (which must be done before release or reuse), and additional income is derived from the sale of the waste heat energy.

Local Heating Systems

There are many types of local heating systems. However, their defining characteristic is that they are located within the structure that they are designed to heat. These systems typically will not have the Btu generation capacity of a central boiler and different types of local heating systems will utilize different types of fuels. Some of the most common local heating systems include unit heaters, convection heaters and radiant heaters.

Unit heaters

These types of heaters are also called forced-air heaters (i.e. Modine® or Reznor® heaters). Unit heaters come in various capacities but units producing 100,000 to 400,000 Btu/hr are most common. Unit heaters commonly burn natural gas or propane but may also burn kerosene or various types of waste oils that are automatically provided to the firebox through a supply line. In these types of heaters, the fuel is combusted in a fuel box, and the hot exhaust is passed through thin-walled metal tubes or hollow panels known as heat exchangers. Heat energy is transferred from the exhaust to the metal of the heat exchanger as the exhaust is vented through the heat exchanger and out of the greenhouse.

A fan behind the unit draws greenhouse air over the heat exchanger and the heat is transferred from the heat exchanger to the greenhouse air. The hot air may be blown directly into the greenhouse or forced through a polyethylene tube (jet tube) that runs the length of the greenhouse. Some types of unit heaters do not have heat exchangers. These types of unit heaters are often used in animal confinements (i.e. chicken houses), garages, factories, or workshops.

If operating at 100% efficiency, all of the fuel burned in the unit heater is converted to heat energy and CO_2. However, if not functioning at 100% efficiency or of the units malfunction, dangerous carbon monoxide (CO) or plant-damaging ethylene gas (C_2H_4) may be produced and exhausted into the greenhouse (see "Atmospheres" learning unit for more information). For this reason, it is generally recommended that unit heaters used in greenhouses have a heat exchanger.

Unit heaters require oxygen in order to burn fuel efficiently. If the greenhouse is too tight, oxygen levels may be too low for the unit heater to operate most efficiently. As a rule of thumb, one square inch opening near the heater should be provided for each 2500 Btu/hr capacity. Often, this is accomplished by running an outside airline to the heater. Most new unit heaters have as part of their standard design such an air line. It is best to work with the manufacturer of the unit heater to insure proper installation and maintenance.

Convection heaters

These are relatively low cost heating units that are usually used in hobby and small commercial greenhouses. These types of heating units typically are used to burn wood, coal or agricultural waste products. They have no internal heat exchanger as do unit heaters. Fuel is burned in a large firebox. The exhaust from the firebox is vented into a large pipe that goes out and down the length (or partially down the length or down the length and back) of the greenhouse before being vented outside. As the hot exhaust moves through the pipe, the heat energy is transferred from the hot exhaust to the exhaust pipe and then to the greenhouse air. In this case, the exhaust pipe essentially serves as the heat exchanger.

When using a convection heating unit, it is best to have a fan at the exhaust end of the vent pulling air out (negative pressure in the pipe) of the exhaust pipe. This pulls the exhaust through faster allowing for more even heat distribution and if a leak in the pipe occurs, greenhouse air will be pulled into the pipe rather than allowing exhaust (which would contain dangerous CO and plant-damaging C_2H_4) to escape into the greenhouse. The same requirements for oxygen need to be followed for these heaters as for unit heaters.

A significant problem with this type of convection heater is that the firebox is at one end

of the greenhouse and the exhaust is typically vented through a single pipe traversing the length of the greenhouse. This can result in significant issues with temperature uniformity and hot and cold spots in the greenhouse are common when using this type of heating unit. Horizontal air flow fans (see Heat Distribution later in this learning unit) may be used to improve temperature uniformity. Another problem with convection heating systems is that fuel (i.e. wood) must be constantly supplied to the firebox and this typically must be done manually for these systems.

Another type of heating unit is actually a hybrid between a convection unit heater and a unit heater. In this type of system, the unit is located at one end of the greenhouse on the floor, has a large firebox and burns coal or wood as in the case of a standard convection heater. However, the exhaust from this unit is vented directly to the outside of the greenhouse. The unit has internal pipes that are heated by the burning of the fuel and a fan behind the unit forces air through the pipes where it is heated before being forced out the front of the unit (similar to a unit heater).

Therefore, this type of unit is essentially a large unit heater, placed on the greenhouse floor that is designed to burn wood, coal or other agricultural waste products. The problem with temperature uniformity still occurs but can be overcome to a great degree through the use of horizontal airflow fans. Additionally, as with standard convection heaters, fuel must either be continuously (usually manually) supplied on a constant basis to the firebox.

Radiant heaters

These heaters are composed of an aluminum tube with a reflector. Fuel (typically natural gas or some type of manufactured fuel) is combusted within the tube so that the tube reaches a temperature of approximately 900° F. At this temperature, the tube emits infrared radiation. The reflector directs the radiation downward. When the radiation strikes a surface (i.e. plants, benches, etc.), the surface absorbs the radiation, and it is converted to heat. After warming, these surfaces give off heat to the greenhouse atmosphere. Because the surfaces are heated first, and the air is heated by convection from surfaces, the air in a radiantly heated greenhouse can be up to 7° F colder than the surfaces.

However, because less energy is wasted heating the entire air volume of the greenhouse, radiant heating units may reduce heating costs by 30 - 50%. However, the initial set up costs can be expensive, and radiant heating units must be placed in such a way that cold spots do not occur in the greenhouse. High-flow horizontal air flow fans are not used to circulate air as this speeds the loss of heat from the surfaces to the atmosphere. However, low-flow horizontal air flow fans or poly-tube fans may be used to maintain some air circulation in the greenhouse.

Solar Heating

Although some of the heat requirement of a commercial greenhouse will be met by incoming solar radiation during the day, this method is not used significantly in commercial greenhouses. The major reasons are cost, degree of control, and reliability. However, solar energy is used in some hobby greenhouses.

Section 3: Heat Distribution for Improving Temperature Uniformity

After heat is generated, it must be distributed throughout the greenhouse facility. Enough Btu must be provided to the greenhouse atmosphere (typically denoted as Btu/hr) to replace the Btu being lost from the greenhouse (to maintain a constant temperature but more Btu to increase temperature). Uniform distribution of heat energy, without having cold or hot spots in the greenhouse, is a very important but sometimes neglected aspect of greenhouse heating. Uneven temperatures can result in uneven crop growth rates, variation in maturation times, and can affect substrate drying rates.

When a central heating system is used to produce hot water or steam, a system of pipes is used to distribute the heat energy throughout the greenhouse. Pipes may be made of cast iron, aluminum or copper. Hot water is usually supplied to the greenhouse at 180° F or 203° F if it is pressurized. Steam is usually supplied at 215° F. Because less resistance occurs in moving steam, smaller diameter pipes can be used for steam as compared to hot water. Also, because steam is delivered at a higher temperature, it provides more Btu than hot water per linear foot of pipe. Therefore, fewer pipes (less linear feet) are needed when using steam. Enough linear feet of pipe must be placed in the greenhouse to allow for enough Btu/hr to be given off to adequately maintain temperature.

The required length of pipe is then distributed throughout the greenhouse structure; typically along walls and under benches if they are present. The length of pipe required will depend on the Btu/hr required and the type of pipe used to distribute the heat energy. For example, if it is determined that a greenhouse structure requires 1,000,000 Btu/hr and 1.50 inch pipe is being used to distribute steam, 4762 ft of pipe (1,000,000 Btu/210 Btu per hr per ft) must be used in the greenhouse. This is the minimum total length of pipe that must occur through the greenhouse and the steam should move through this piping before exiting the greenhouse.

Stacked pipes (placed in layers along walls) are less efficient than single pipes. If pipes are stacked, additional pipes will be required to compensate for the reduced efficiency. As is demonstrated in the table below, the higher the temperature of the pipe or the greater the diameter of the pipe, the greater the number of Btu given off per linear foot of pipe. Finned pipes are more efficient at heat transfer than smooth pipes due to their

increased surface area. Finned pipes may transfer four or more times the amount of heat as a smooth pipe. The advantage of finned pipes is that less pipe is required. The disadvantage of finned pipes is that they release more intense amounts of heat in a small area which can create hot spots.

Heat Available From Different Pipe Sizes Using Steam and Hot Water at Different Temperaturesz

Heat Source	Pipe Diameter	Btu/hr/ft
Steam at 215° F	1.50 inch	210
Steam at 215° F	1.25 inch	180
Hot water at 180° F	2.00 inch	160
Hot water at 203° F	2.00 inch	200

z Assumes a 60° F inside greenhouse air temperature.

The first approach to creating uniform temperature throughout the greenhouse is pipe placement. The required length of pipe should be distributed throughout the greenhouse

along the walls and under the greenhouse benches.

If a central heating system is used and the pipes placed along the lower walls and under greenhouse benches, the warm air rises, and as it does, it cools. This creates temperature stratification. Cool air in the gable area of the greenhouse descends down the inside walls of the greenhouse and creates cold pockets along the greenhouse walls. Horizontal airflow fans (HAF), placed below the gable and along the length of the greenhouse and in opposing positions to create a circular air flow pattern, create a horizontal air circulation pattern and force warm air to move down the length of the greenhouse and prevent temperature stratification.

When unit heaters are used, heated air is directly discharged into the greenhouse. The primary concern then becomes one of evenly distributing the heated air. If unit heaters are used to heat greenhouses, a temperature gradient can occur along the length of the greenhouse. Temperatures will be warmer closer to the unit heater. Several strategies can be employed to minimize the temperature gradient along the length of the greenhouse. The first is to use multiple unit heaters placed at opposite ends of the greenhouse in opposed positions.

In addition to providing heat at both ends of the greenhouse, the opposed airflow assists with mixing of the greenhouse air and improves temperature uniformity. Where relatively long greenhouses are used, HAF fans may also be added to help move warm air down the length of the greenhouse and to further promote the mixing of air. In some cases, the unit heater may be connected to a polyethylene jet tube. The warm air is first forced down the length of the jet tube. After the jet tube fills, the warm air evacuates the tube from holes along its side. Jet tubes may also be used in combination with HAF fans.

Often in spring and fall, heating is required at night and cooling required during the day due to solar heating. The fan of the unit heater and polyethylene tube can be used (with fire box and fuel source turned off) for cooling in these situations if outside louvers are included. The louvers located behind the unit heater are opened and the fan turned on so that cool outside air is forced into the polyethylene tube. Additionally, the louvers can be closed and the fan turned on to improve internal greenhouse air circulation.

Some specialized heating systems use polypropylene or rubber tubes to circulate hot water in close proximity to the root system of the plants. There are many variations to this system, but the most common is the Biotherm® system. This system is most commonly used for increasing substrate temperature during propagation rather than general greenhouse heating.

Section 4: Fuel Sources

There are many considerations when deciding upon a fuel source. These include availability, cost, price volatility, pollution regulations, storage requirements, equipment requirements, boiler requirements, and maintenance requirements.

When determining fuel cost, all costs of using a given fuel must be considered. This includes handling and storage equipment required as well as maintenance costs. Additionally, different fuels contain different amounts of energy. Therefore, when evaluating the cost of the fuel, the cost per Btu (or per 1,000,000 Btu for example) should per determined and not the cost per weight or volume of the fuel. This will allow a more direct comparison of cost among fuels.

Common Fuel Sources Used for Heating Greenhouses and Their Characteristics

Fuel Source

Characteristics

Natural Gas

Usually low cost but prices fluctuate; clean burning; no storage tanks required; simple inexpensive system with generally low maintenance costs. Commonly used in greenhouse.

Propane and Butane

Similar to natural gas but more expensive; price can be volatile and storage tanks are usually required. Often used for greenhouse where natural gas is unavailable.

Oil (grade No.2 or lower)

More expensive than natural gas; requires more boiler maintenance because it does not burn as clean as natural gas or propane; storage tanks required.

Coal

Generally low in cost if readily available; generates significant pollution; large storage area needed; moving and loading equipment required; significant boiler cleaning and maintenance required.

Wood chips

Often low cost if available; need secure source; need large storage area, handling and

loading equipment; significant boiler maintenance and cleaning required.

Logs

Similar to wood chips but require different handling systems.

Electric

Expensive; limited to small or hobby greenhouses.

Estimates of BTU Output Expected From Different Fuel Sources (corrected for efficiency)

Anthracite Coal

8,300 Btu/lb

No. 1 Fuel Oil

93,000 - 96,000 Btu/gallon

No. 2 Fuel Oil

95,000 - 99,000 Btu/gallon

No. 4 Fuel Oil

95,000 - 104,000 Btu/gallon

Natural Gas

750 Btu/ft3

Propane

1,900 Btu/ft3

Dried Wood Chips

5,000 Btu/ft3

Section 5: Calculating Greenhouse Heat Requirements

In most cases greenhouse managers will not need to determine greenhouse heating requirements. In most cases greenhouses are custom designed or predesigned greenhouses are purchased. The greenhouse design and construction company will have determined heating requirements for the specific greenhouse for different locations and environmental conditions. However, it is useful to have a basic understanding of how greenhouse heating requirements are determined.

The underlying principle for determining the heating requirement of a greenhouse is to replace the Btu that are lost from the structure (Btu/hr) so as to maintain the temperature within a desired range. Typically, heat loss through radiation is ignored since the amount is negligible. Therefore, only heat loss through conduction and infiltration/exfiltration are usually determined. These losses are determined for the coldest expected temperatures occurring at night. These provide maximum values for the heating capacity that should be required during the coldest time of the year. During the day when solar input provides additional heat energy or during warmer times of the year, the full heating capacity may not be utilized. It is also common to actually install a somewhat higher heating capacity than required to provide some level of "insurance" heating capacity.

An example heating capacity example follows. There are different variations to these calculations, but the example below is typical and provides an examples of the factors considered when determining required heating capacity.

ht = hc + hsa
where:
ht = total heat loss from greenhouse
hc = heat loss by conduction
hsa = sensible heat loss by mass transfer
hc = AU(ti-to)W
where:
hc = heat loss by conduction
A = surface area
U = heat transfer coefficient (to be taken from table of standard values below)
ti = desired inside air temperature
to = minimum outside air temperature
W = wind correction factor
hsa = 0.02(ti-to)(V)(M)(W)
where:
hsa = sensible heat loss by mass transfer
ti = desired inside air temperature
to = minimum outside air temperature
V = greenhouse volume (to be calculated)

M = air exchanges per hour (value taken from table of standard values below)
W = wind correction factor (value taken from table of standard values below)

Heat Transfer Coefficient for Various Glazings and Surfaces (U)

Surface

Btu/ft2/hr/oF difference

Glass, single layer

1.13

Glass, double layer

0.65

Polyethylene film, single layer

1.15

Polyethylene film, double layer

0.70

Fiberglass

1.00

Bi-wall polycarbonate

0.65

Bi-wall acrylic

0.65

Concrete block, 8"

0.51

Concrete block with foam urethane

0.13

Poured concrete, 6"

0.75

Air exchanges per hour for various greenhouse types (M)

Greenhouse type

Air exchanges per hour

Metal greenhouse with glass

1.08

Wood and steel greenhouse with glass

1.05

Wood greenhouse with glass, tight

1.00

Wood greenhouse with glass, moderately tight

1.13

Wood greenhouse with glass, loose

1.25

Wood greenhouse with FRP

0.95

Metal greenhouse with FRP

1.00

Metal greenhouse with double glass

0.70

Metal greenhouse with single layer of polyethylene

1.00

Metal greenhouse with double layer of polyethylene

0.70

Correction factors for wind speed (W)

Wind speed (mph)

Correction factor

less than or equal to 15

1.00

20

1.04

25

1.08

30

1.12

35

1.16

As an example, the Btu requirement of an A-frame greenhouse is determined below. The greenhouse is a 40 ft x 100 ft, glass-glazed, metal frame greenhouse, and of tight construction. The gable is 8 ft from the eave to the peak. It has an 8 ft wall with 2 ft of the wall being a 6-inch concrete block curtain wall. The maximum expected wind velocity is 15 mph. The minimum expected low temperature is 0oF, and the minimum

desirable inside temperature is 60° F.

The surface area glazed with glass is 8000 ft2, and the surface area for the curtain wall is 560 ft2.
The volume of the structure is 48,000 ft3.

Therefore:
hc = 8000(1.13)(60)(1.0) + 560(0.51)(60)(1.0) = 559,536 Btu/hr
hsa = 0.02(60)(48,000)(1.08)(1.0) = 62,208 Btu/hr
ht = 559,536 Btu/hr + 62,208 Btu/hr = 621,744 Btu/hr

An example is outlined below for a 30 ft x 100 ft quonset greenhouse (covering is 47 ft wide), with a double polyethylene covering. The maximum expected wind velocity is 15 mph. The minimum expected low temperature is 0oF, and the minimum desirable inside temperature is 60° F.
The following equations can be used to estimate surface area and volumes of quonset greenhouses:

Circumference of a circle = 2πr
Area of a circle = πr2
Total surface area of a cylinder = (2πrH) + (2πr2)
Volume of a cylinder = πr2H
Therefore:
The surface area glazed with polyethylene film is 5409 ft2.
The volume of the structure is 35,325 ft3.
and:
hc = 5409(0.70)(60)(1.0) = 227,178 Btu/hr
hsa = 0.02(60)(35,325)(0.70)(1.0) = 29,673 Btu/hr
ht = 227,178 + 29,673 = 256,851 Btu/hr

As can be seen in these examples, the basic approach is to determine volume of surface area and volume of the structure. The Btu/hr requirement for a standard structure is then corrected for those variables that increase (greater temperature differentials, higher wind speeds, higher U values for glazing, poorly built or older or poorly structure) or decrease the rate of heat loss. These example calculations also demonstrate the large number of Btu/hr heating capacity that may be required. Small greenhouses such as those demonstrated in these equations required hundreds of thousands of Btu/hr. A large greenhouse or greenhouse complex will usually require millions of Btu/hr.

Section 6: Methods of Heat Conservation

Greenhouse design

Minimizing the exposed surface area can reduce heat loss. This is primarily accomplished through the use of gutter-connected designs.

Glazing selection

Heat loss can be reduced by selecting glazings with low thermal conductance values.

Wall insulation

Heat loss may also be reduced by including insulated curtain walls along the lower three to four feet of the greenhouse walls. In northern climates, the entire north wall is converted into a curtain wall since the light loss is minimal and heat savings significant.

Thermal screens

Polyester, cloth, or polyethylene screens that can be pulled closed at night reduce heat loss through the roof panels of the greenhouse.

Windbreaks

Windbreaks reduce the effect of wind on heat loss and thus can reduce heat loss from the greenhouse. However, windbreaks (i.e. high walls or trees) can also reduce light entering the greenhouse if placed too close to the structure.

Close air leaks

Broken panels, loose panels, poorly sealed doors, and other openings in the greenhouse structure increase the mass air flow (infiltration and exfiltration) and increase heat loss.

Equipment Maintenance

Regardless of the type of heating system utilized, proper maintenance of the entire system is critical. Not only will maintenance maximize efficiency of the heating system but will protect against a malfunction that can result in the release of ethylene and/or carbon monoxide into the greenhouse. Maintenance should include appropriate cleaning, checks of the air intake, checks of the exhaust system, checks of the fuel line, checks of fans, checks of the burner system and the heat exchanger, calibration of the thermostat, and any other maintenance items prescribed by the manufacturer.